LaserCom Pointing Acquisition and Tracking Control using a CCD-based Tracker

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ABSTRACT

A CCD-based spatial acquisition and tracking subsystem has been developed to perform both spatial acquisition and tracking functions for a lasercom instrument. By operating the CCD in the "windowed" read mode, the detector can achieve both wide field of view required for spatial acquisition and the high update rate needed for effective platform jitter compensation. Furthermore, spatial tracking subsystem based on the CCD tracker requires only one steering mirror to perform both line-of-sight stabilization and point ahead functions, and provides means to optically close the point ahead cent rol loop wit hout addi tional sensors. When incorporated into the lasercom system designs, the array tracking concept can lead to reduced system complexi ty. For future commercial or government applications of lasercom technology in Earth orbit, design simplifications offered by the CCD-based acquisition and tracking subsystem can lead to lower implementation cost and increased commercial viability.

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1. INTRODUCTION

Spatial acquisition and pointing problem is critial to lasercom system because of the narrow transmit beamwidth. Inaccurate beam pointing can result in large signal fades at the receiving site and a severely degraded system performance. This problem is compounded by the fact that the platform jitter presented in the spacecraft due to deadband cycle and random platform jitter are much larger than the transmit beamwidth. As a result, a dedicated pointing control subsystem is required to reduce the signal loss due to pointing error. Such a subsystem must be capable of first acquiring the receive beacon signal in the presence of large attitude uncertainty, and then delivering a accurately pointed transmit signal, The required pointing accuracy of the transmit signal is typically less than $\approx 20\%$ of the diffraction-limited beamwidth or, equivalently, on the order of microradians. In contrast, the beam pointing requirement for a RF communication system is several orders of magnitude less stringent.

in the past, designs of lasercom systems generally achieved the desired pointing accuracy by using a directionally sensitive detector such as a quadrant avalanche photodiode (QAPD) to measure the angular error between the detector line-of-sight and the beacon direction [1-2]. The error was then fed back to a high bandwidth steering mirror to stabilize the detector line-of-sight along the beacon direction. A second point-ahead mirror in the transmit beam path is then used to provide the required pointing offset between the transmit and receive signals. Since the quadrant detector has a limited field-of-view, a separate, larger format detector was usually required to provide the wide field of view coverage during the acquisition process. Furthermore, in order to properly relay the optical signals between the steering mirrors and detector focal planes, additional optical relay elements are required that further increase the system complexity. The additional complexity introduced by the pointing control subsystem can quickly erode the inherent mass advantage of the lasercom system, and can lead to an increased reliability engineering problem and a higher system cost.

With the advances in array detector technology, conceptual simplification of the lasercom tracking and acquisition subsystem can be achieved without sacrificing the system performance. This is because a pixelated detector can provide wider field of view coverage, thus simplifying the spatial acquisition process. A wide field of view system can also permit tracking of the receiver beacon off axis; thus permitting the system to be implemented with only one steering mirror. Several systems have been designed or implemented in the past to demonstrate the array tracking concept. In order to achieve the high bandwidth required for platform

jitter compensation, these past systems tend to employ small format devices [3] or detectors with complex readout arrangements [4]. For example, a multiple readout port device to permit rapid readout of the device, and complex post detection processing circuit to ensure proper signal processing. The additional complexity tends to drive the mass and power margin and thus reduces the applicability of the array based tracking concept.

One reason for the high detector speed requirement, and thus the need for a multiple readout port device, is the requirement to effectively compensate the platform jitter at high frequencies. By realizing that passive isolators can be used to decouple the platform jitter noise from the instrument, the required bandwidth of the detector can be reduced. Additionally, by realizing that only pixels near the target needs to be processed for effective tracking, the bandwidth of the single readout device can be improved such that it satisfies the tracking requirements.

The acquisition and tracking subsystem of the Optical Communications Demonstrator (OCD) will employ the single array detector tracking concept. A single, large format device will be used to provide both wide field of view acquisition as well as fine tracking of the remote target beacon. Furthermore, a single readout port device will be used to simplify the detector and post detection electronics design.

2. ARRAY ACQUISITION AND TRACKING CONCEPT

in order to achieve the desired pointing accuracy, an auxiliary pointing sensor and a beam steering mechanism to compensate for platform vibration must be an integral part of any lasercom system design. sensing of pointing error is accomplished with the aid of a beacon signal from the receiving site. The beacon signal defines a directional reference from which any deviation produced by the platform disturbance can be referenced. The beacon direction and the relative velocity vector between the transmit and receive platforms define the desired direction to transmit the downlink signal. By sensing the deviation from the desired pointing angle, and feeding back the error signal to the beam steering elements, the lasercom system can stabilize the pointing even if the platform jitter is several times larger than the required pointing accuracy.

A conceptual block diagram of the array-based tracking system is shown in Figure 1. A remote beacon laser is imaged by the telescope optics onto the focal plane array. By reading out the area of the detector containing the beacon signal and calculating the image centroid, the angular direction of the beacon can be accurately deduced relative to the optical axis of the system. A small amount of the transmit signal can also be imaged onto the acquisition detector and the location of the transmit signal can be measured relative to the optical axis. The distance between the two image spots in the focal plane is a direct measure of the relative angular offset between the transmit and beacon signals. By sensing any difference between this measured, instantaneous point ahead angle and the desired point ahead value, the instrument can derive a real time control signal to maintain pointing of the transmit signal.

The subsequent beam steering control can be achieved using a tandem of high bandwidth steering mirror and wide dynamic range gimbals, Large amplitude disturbances such as the dead band cycle of the spacecraft are first removed using an coarse pointing gimbal. A fast steering mirror in the optical path is then used to compensate for the high frequency, small amplitude disturbances. The gimbal removes the bias and maintains the steering mirror at the middle of its dynamic range. During the initial acquisition, the gimbal is also used to orient the instrument line of sight for acquisition.

The concept of the OCD pointing control subsystem described above requires only one steering mirror and one detector. Instead of stabilizing both the receive and transmit lines-of-sight, only the relative angle between the transmit and receive beams will be stabilized. The pointing control approach is further simplified by providing optical feedback for the point ahead angle, thus eliminating **the need** for additional sensors to measure the point ahead angle. 1 n contrast, a QAPD-based tracking subsystem generally requires a high bandwidth mirror for beacon line-of-sight stabilization, and a separate point ahead mirror for point-ahead compensation. Furthermore, either a large format acquisition detector or a complex scanning acquisition

sequence will be required for initial spatial acquisition. Additionally, since there was no direct optical feedback to measure the point ahead angle, sensors were required to measure and control the point ahead angle.

The array detector tracking concept can also be implemented by positioning the steering mirror in the beacon path, and aligning the transmit signal such that the transmit line of sight overlaps the beacon path as shown in Figure 2. By tracking the beacon to a location away from the detector center, therefore, the system can control the point ahead accurately. This method provides direct steering of the transmit and receive beams, and has the added advantage that, with a wider field of view steering mirror, the gimbal accuracy requirements can be relaxed. Nevertheless, the two spot tracking implementation shown in Figure 1 provides added advantage of boresight calibration which can simplify the required transmit/receive paths alignment, and was therefore selected for implementation.

Shown in Figure 3 is a block diagram of the two-spot tracking control loop. The detector, images both the beacon signal and a portion of the transmit signal. The output digital data is then relayed to a control processor which computes the positions of the image centroids and hence the instantaneous point ahead angle. This point ahead angle is then compared to a reference point ahead angle and the difference is fed into a compensation filter which calculates the control needed for the fine steering mirror. At the same time, the position of the beacon signal is fed to the gimbal control circuit which stabilizes the poisition of the gimbal spot on the focal plane.

3. IMPLEMENTATION

The control system described in Figure 3 requires development of a dedicated CCD camera capable of supporting high update rate, a high speed control processor with camera interface circuit, and the control algorithm.

It was decided early in the development stage that the desired field of view will be achieved using large format charge couple devices (CCD) instead of the charge injection device or active pixel sensors. Although these other devices offer random access capability, the maturity of the technology lags behind that of the CCD and consequently is not expected to be applicable for lasercom system development for the next several years.

To operate the detector in tracking mode, it is desirable for the CCD to have high charge transfer efficiency and high quantum efficiency at the wavelength of interest. Furthermore, the device should be capable of being clocked at high speed, and should possess near 100% fill factor for effective centroiding. The format of the detector is chosen as a function of the desired field of view, the pixel field of view, focal length of the optics, and the expected resolution of the centroiding algorithm. It was determined that a 100x1OO detector can provide sufficient field of view (1 mrad) and, at the same time, can permit a simple centroiding algorithm to achieve the desired pointing accuracy.

The read noise requirements of the CCD can be readily deduced from the required centroiding accuracy and the expected beacon fluence level. Given the demonstration nature of OCD, the beacon intensity requirements has been relaxed to 100nW/m^2 or, effect ively, $7x1 0^5$ received signal photons per frame. Given the detector quantum efficiency of 40% at 800nm, the expected centroiding error due to detector read noise will be a small fraction of the pixel size for any reasonable read noise level[1]. A more serious contribution to the

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[1] Simulation has shown that the rms centroiding error is related to the rms read noise and the total detected signal photons by

$$\Delta r_{rms} \approx K_0 n_{rms} / N$$

centroid error is the expected fluctuation in the background level within the beacon window field of view. An estimate based on the nominal sky irradiance of 0.6W/m.nm.srad shows that over the 5000μs window, the maximum expected background flux is approximately 2000 detected photons/pixel/frame. The contribution of the background photons to the centroid bias is estimated, under worst case, to be approximately 0.07 pixels. This is consistent with the pointing budget allocated for the detector noise.

The frame rate requirement for the CCD is driven by the expected jitter spectrum the tracking system is expected to attenuate. For effective compensation of the platform jitter, a frame rate on the order of 5000Hz is typically desired. To achieve such a frame rate, a dedicated detector and processing circuit will be required. However, if passive damper can be employed to remove some of the higher frequency component of the platform jitter noise, then a frame rate on the order of 2kHz will be sufficient to provide accurate pointing and tracking of the return signal.

In order to operate the CCD in the tracking mode, it is desirable that the readout time of the device be small compared to the integration time such that the effect of image blurring due to vertical transfer is limited. Furthermore, it is desirable to operate frame transfer/in~age storage devices such that the readout can be carried out independent of frame integration. Conventional CCD imaging systems read out every pixel in the detector. The maximum vertical and horizontal transfer clock speed is typically on the order of 5-10 MHz. Because of the large number of individual pixels in an array detector, a detector with the required field of view and pixel resolution will generally have a relatively slow frame read speed. An alternative is to read out only a portion of the pixels that are critical to the tracking, namely the areas around the beacon and transmit laser spots. At the beginning of the read cycle, the image zone is transferred into the storage zone such that integration can be conducted independent of the subsequent image readout. A "windowed" read operation can then be performed by clocking the vertical transfer lines of the CCD such that only the lines containing the areas of interest will be read on a pixel-by-pixel basis; whereas other lines will be skipped without being read. Shown in Fig. 4 is an illustration of the high speed clocking concept.

Because of the proof of concept nature of the system, a commercial CCD (Thomson 7863) was selected over a dedicated CCD because of reduced cost, schedule, and technical risk. The Thomson CCD has a larger form factor than required (384x288 rather than 100x1 00). Furthermore, it has a slower vertical transfer rate than desired (2MHz vs 5MHz). Nevertheless, an implementation which achived the desired 2kHz update rate was successful by limiting the tracking area to the lower 100x100 active area of the CCD.

Implementation of the tracking control involves the design and development of both the camera head electronics and the processing electronics. Shown in Figures 5 and 6 are block diagrams of the camera head electronics and the control interface electronics, respectively. The camera head electronics include the CCD, the clock drivers, video amplifier, and the output analog to digital converter. Correlative double sampling is implemented to reduce fluctuation of the background level. Unlike conventional cameras that have to incorporate clock timing control to match the display, the camera electronics can be under direct control of the processor, thus simplifying the design.

In order to achieve the maximum frame rate possible, it is desirable that the pixel processing be achieved at maximum speed. This is accomplished by two design features. First, the pixel data is processsed on the fly, i.e., without being stored in memory after readout, thus eliminating the memory storage/retrieval cycles typically associated with image processing. Shown in Figure 7 is a block diagram of the centroiding algorithm which divides into once a pixel, once a line, and once a frame computations. Second, the readout of the CCD is synchronized to the processing by using an asynchronous FIFO. A programmable gate array is used to initiate the horizontal line transfer after each vertical transfer pulse. The pixel output is then stored in the FIFO at a constant 10MHz speed. The processor then accesses the FIFO at the maximum rate when it is

where K. is a constant which is weakly dependent on the image spot size and the actual image location (versus the pixel boundary), and N is the total number of signal photons within the centroiding window. When the image spot size is ≈2 pixels, the constant K. is approximately 11.0.

ready to handle the data. The usc of FIFO synchronizer eliminates the waiting time between the detector output and pixel processing. For example, in between pixel lines, the processor computes the line average while the detector can be reading the pixels independent of processor control. When the processor is ready, it can then skip the necessary pixels at a higher rate than the 8M Hz pixel clock. The only control the processor needs to issue arc therefore the vertical transfer clocks and the horizontal read signals.

The required numerical processing of a high rate centroid process can impose a stringent demand on the processing power requirement for the tracking and acquisition subsystem. Onc possible method is to implement a dedicated processor which controls the detector and computes the centroids. The required house keeping functions and control loop computation can then be handled by a second, less powerful, processor. Such an archi tecture offers advantages of reduced demand on the processor. However, the required inter-processor communication and synchronization can be rather complicated. An alternative is to implement most of the control in onc single processor. A single processor implementation offers the advantage of simpler software design and reduced data communications and control complexity. However, it dots impose a more stringent demand on the processing power of the control processor. Fortunately, with the availability of high speed floating point digital signal processors currently available off the market, such an implementation is quite practical. After evaluating the various processors available, it was decided that a commercially available DSP board (Ariel Cyclops) will bc used for the processing of the OCD tracking subsystem. The Cyclops employs a TMS 320C40 processor that provides a maximum processing throughput of 50 MFLOPs. Furthermore, the processor has built-in timers for frame rate control, and DM A channels that can be used for controlling the camera.

Shown in Figure 8 is a typical control flow of the tracking algorithm. At the beginning of every frame period, the CCD is set to transfer the image from the image plane to the storage plane. Note that for a frame transfer CCD, the processor need not bc processing the image ccntroids when the detector is transferring the image between the image plane and the storage plane. The processor is then available to perform the necessary house keeping tasks such as (a) updating the communications port to monitor any command uplink, (b) computing the desired point ahead angle based on the point ahead angle supplied by the ephemcridcs, current orientation of the host relative to the standard frame, and current position of the gimbal, (c) monitoring the status of the instrument, and (d) downlink any status data.

At the end of the frame transfer operation, the centroiding process will bc initiated. This is accomplished by first rapidly shifting (vertically) to the line of interest. Each successive line is then read out, pixel by pixel, into a first-in-first-out buffer. Pixels that arc in the tracking window arc then processed to compute the following quantities: (a) number of pixels above tracking threshold, (b) integrated intensity, (c) ccntroid position, (d) average intensity along the window border, and (e) new window coordinate based on the current centroid position. The ncw window coordinate is computed such that the centroid is always near the center of the window. This ensures accurate tracking of the window. The number of pixels above threshold and total integrated intensity serves as auxiliary information that can be used for clutter rejection and lost track detection. Finally, the average intensity along the window boarder provides an indication of the background intensity which can be subtracted from the current pixel value. For the OCD implementation, this background intensity value is assumed to be uniform throughout the window, and is subtracted off in the subsequent frame processing.

At the end of centroid computation, the control signal is calculated based on the current point ahead value and the desired point ahead value. The control signal calculation, which is performed via three concatenated second order IIR filters, is accomplished within 20µs. This signal is then fed into the digital-to-analog converter to drive the mirror.

6. SUMMARY

CCD-based spatial acquisition and tracking subsystem can significantly reduce the design complexity of a spaceborne lasercom system. By offering a large field of view to cover the initial attitude uncertainty of the

host spacecraft, the detector can be used for initial acquisition of the remote beacon. With the use of a windowed read algorithm, the detector can provide a sufficiently high position update rate to track the beacon in the presence of platform jitter. Furthermore, a detector array can pm-nit direct measurement of the transmit-receive pointing offset which can be used to control the point-ahead angle without additional sensors.

By realizing that a lasercom system only needs to stabilize the relative pointing offset between the transmit and receive signals, and not the individual signals, the array-based tracking concept can be extended to an optical design which requires only one steering mirror for both platform jitter tracking and point-ahead compensation. The reduction in design complexity can lead to a reduced system cost and an improved system reliability. Furthermore, it can permit the implementation of a new generation of lasercom instruments capable of realizing the inherent advantages of optical frequency communication systems.

7. ACKNOWLEDGMENTS

8. REFERENCES

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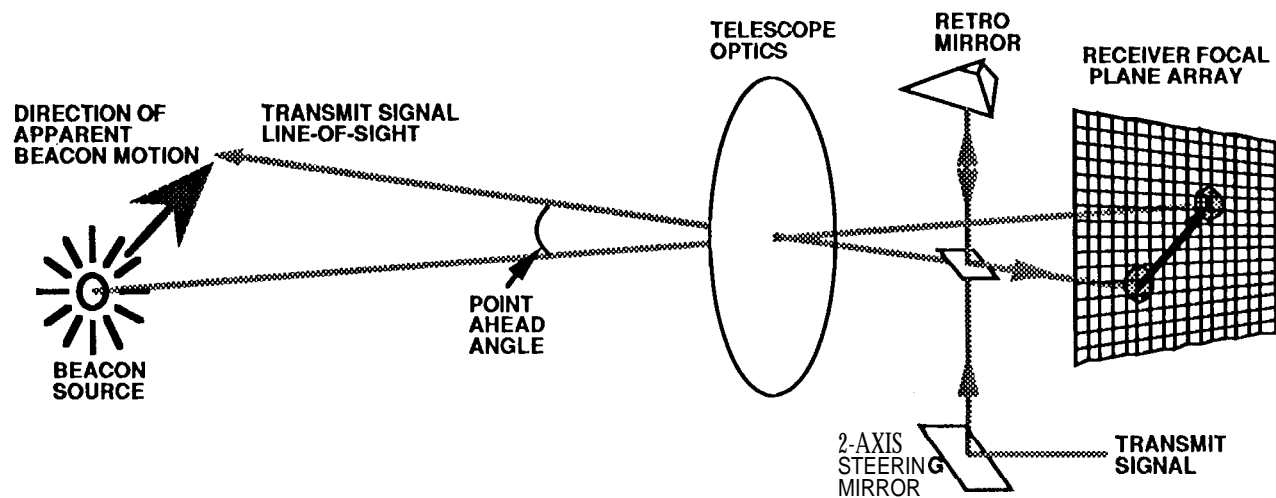
Figure 1. Two-spot spatial tracking using a single array detector.
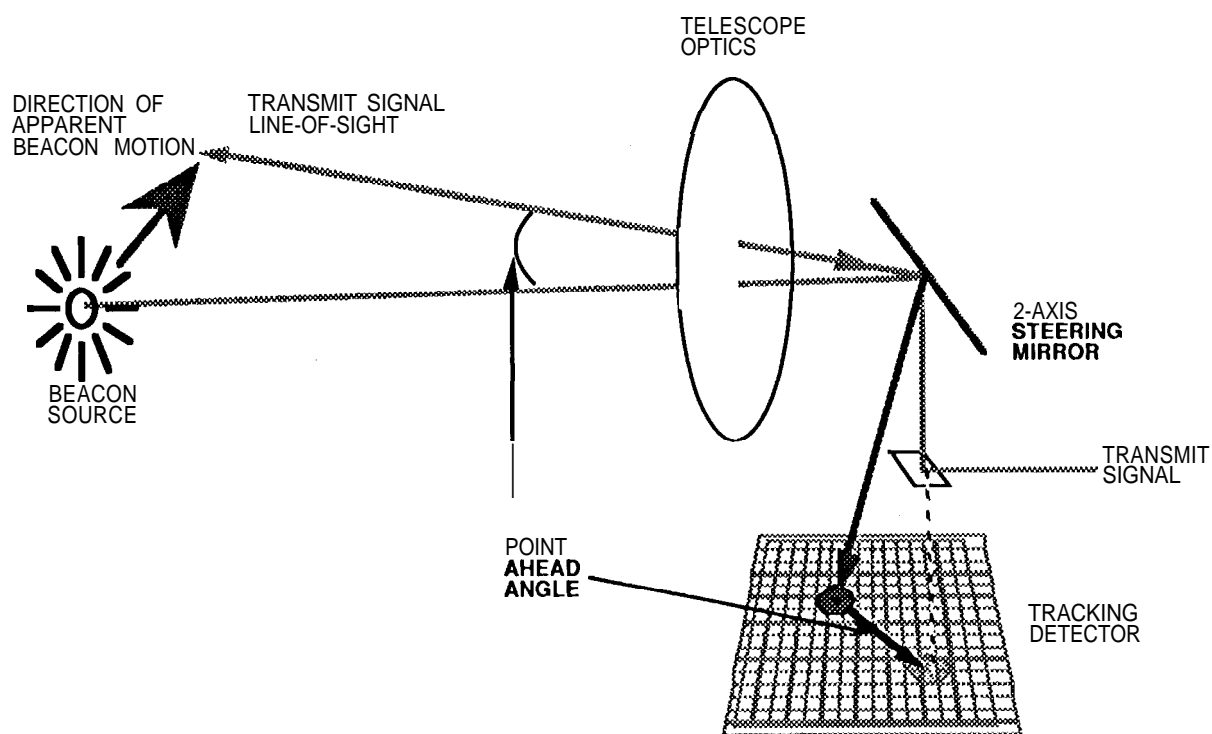

Figure 2. Single spot spatial tracking using an array detector.

Figure 3. Block diagram of a CCD-based tracking control loop.

1. Transfer image into storage zone

2. Rapid vertical transfer until the first line of the window is in the horizontal shift register

3. Rapid horizontal transfer until the first pixel to be read is at the output gate

4. Read out the desired number of pixels in the line

5. Vertical shift when last pixel of the window is read

6. Repeat 3-5 for every lines in the window

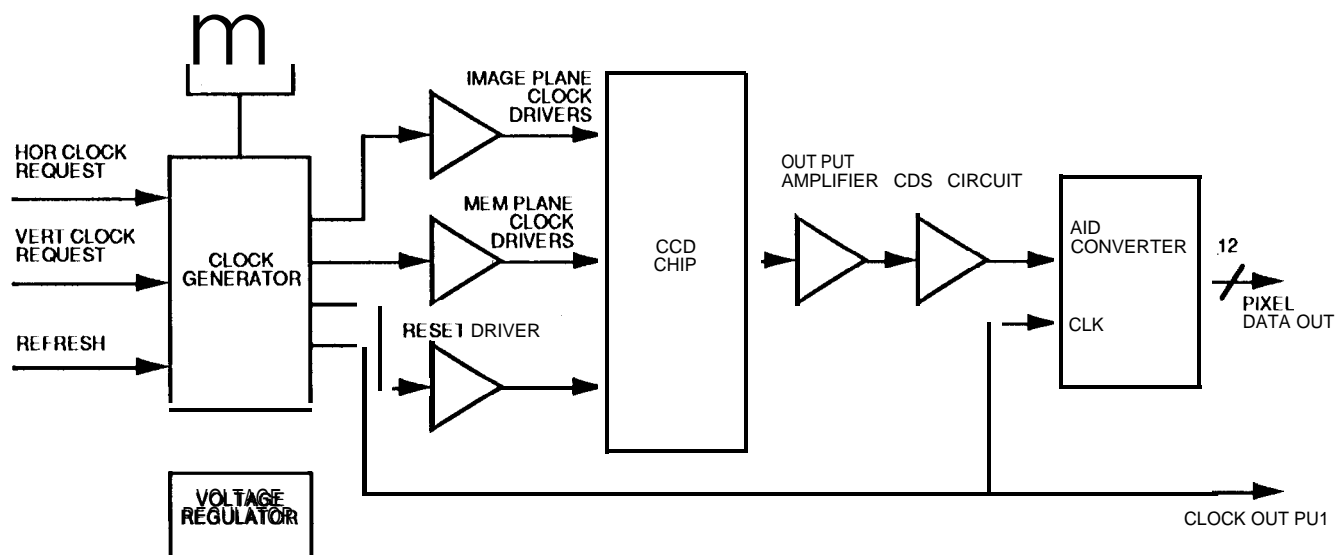Figure 4. Windowed mad algorithm for an image transfer CCD.

Figure 5. Block diagram of the camera electronics.
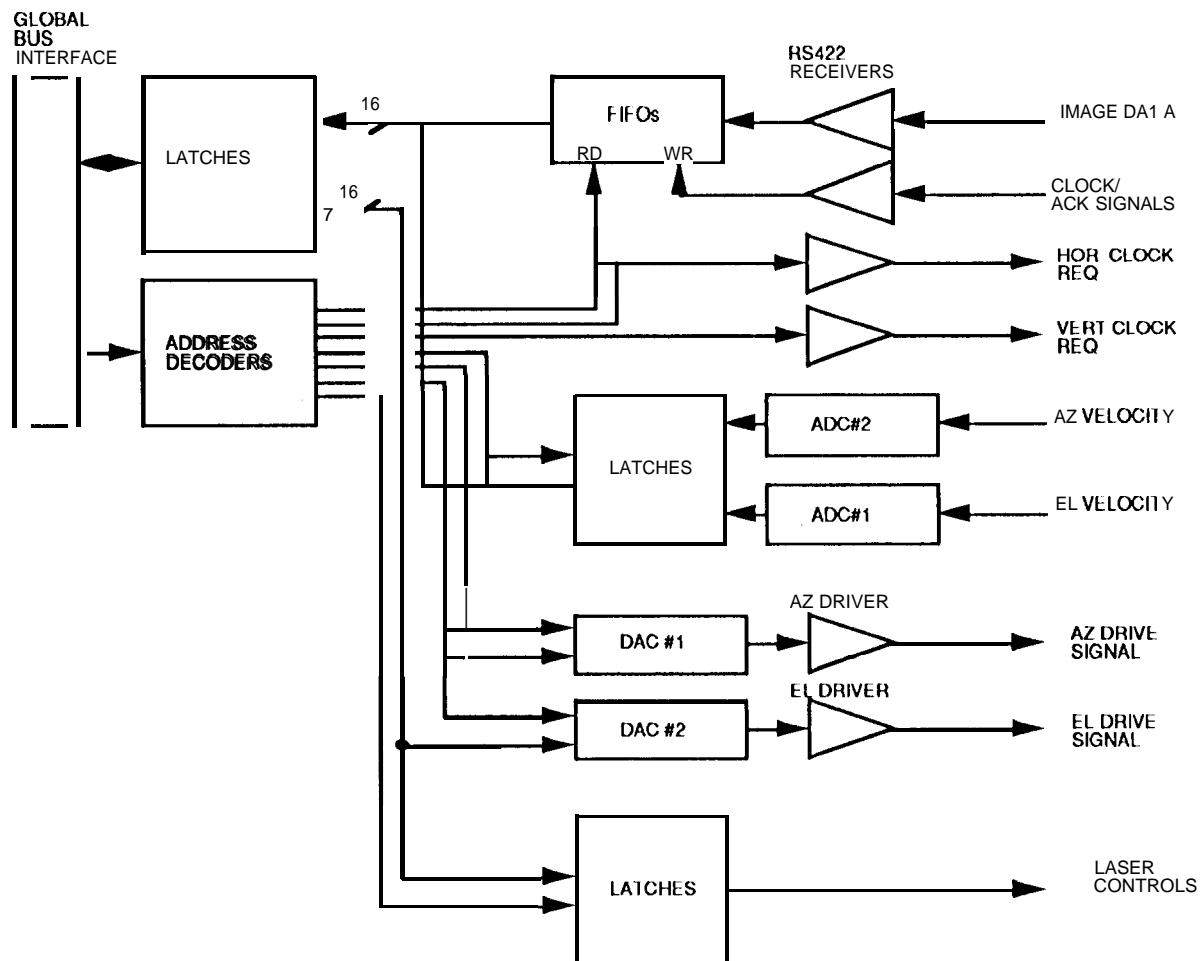

Figure 6. Block diagram of the tracking control interface electronics
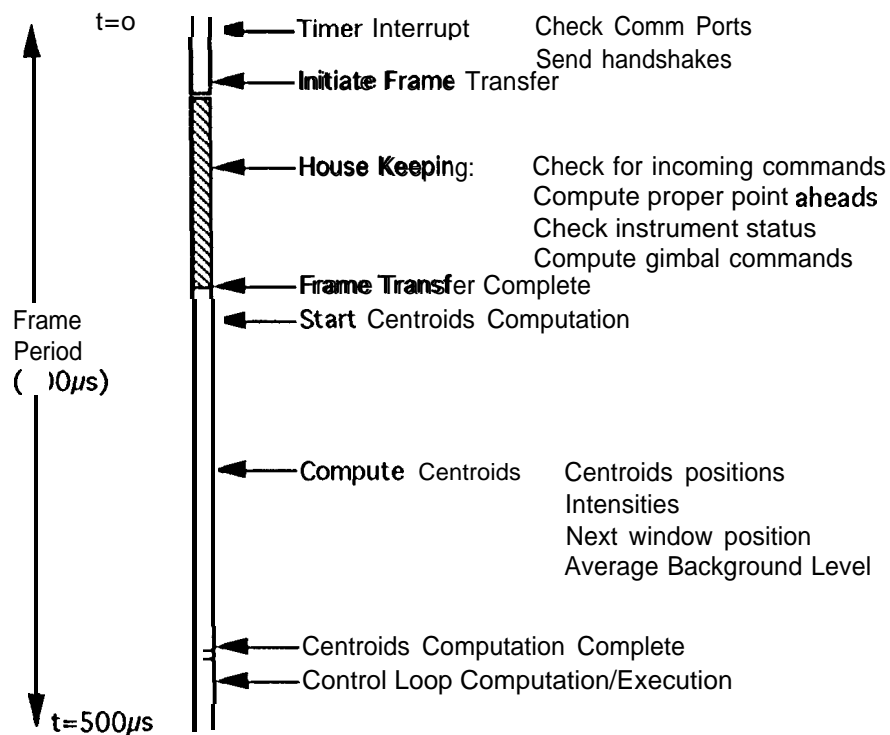
Figure 7. Centroid algorithm

Figure 8. Control flow diagram of the tracking control loop.

D0748-G

CENTROID ALGORITHM

/PIXEL PROCESSING

1/LINE PROCESSING

1/FRAME PROCESSING

READ A/D INTO DSP

WRITE TO MEMORY

IS PIXVAL > THRESHOLD ?

EXIT

ACCUMULATE NO. PIXELS EACH WINDOW

ACCUMULATE Σ PIXVAL IN LINE BY WINDOW

ACCUMULATE Σ PIXVAL X HOR ADD BY WINDOW

HORIZONTAL ADDRESS

ACCUMULATE PIXSUM BY WINDOW FOR FRAME

VERTICAL ADDRESS

ACCUMULATE Σ VERT ADD X PIXSUM IN LINE

WINDOW OCCUPANCY

VERTICAL CENTROID VALUE

HORIZONTAL CENTROID

LORAL

Electro-Optical Systems